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Abstract

Lightweight roofing systems made of thin and high strength steel roof sheeting and battens are commonly used in low-rise buildings. However, they often fail frequently at their screw fastener connections during wind storms due to inadequate connection capacities. Two localised failures, known as pull-through and pull-out failures at the screw fastener connections, have been the root cause for extensive loss of roofing systems under high wind uplift loads. Such premature connection failures often cause partial or even complete loss of steel roofing systems and severe damage to building contents. Therefore many experimental studies have been conducted to investigate the pull-through failures of roof batten to purlin/rafter connections and the pull-out failures of roof sheeting to batten and roof batten to rafter connections. The roof batten connections involve multiple (two or four) screw connections between the two bottom flanges of roof battens and rafters. This paper reports the details of experimental studies on one of the localised screw connections failures, the pull-out failures. More than 750 small scale pull-out tests were conducted for this purpose using a range of screw fastener sizes and many thicknesses of thin steel roof battens and purlins. This paper presents the important details of the experimental studies and the pull-out capacity data obtained from the tests. It then presents suitable design equations and capacity reduction factors to accurately determine the pull-out capacities of both single and multiple screw fastener connections commonly used in steel roofing systems. They can also be used for the screw fastener connections in steel wall cladding systems.

Keywords: Cold-formed steel roof and wall systems, Steel roof battens and purlins, Screw fastener connections, Wind loads, Localised pull-out failures, Experimental study, Design equations

Introduction

Cold-formed steel roofing systems made of high strength and thin steel are commonly used in low-rise building construction. Thin steel roof sheeting is screw fastened to the top flanges of roof battens whose bottom flanges are screw fastened to rafters or trusses (Fig.1). The high wind uplift loads on these light gauge steel roofing systems during wind storms must be transferred safely. However, they often cause premature failures of these roof connections, which lead to extensive loss of steel roofing systems and damage to building contents. Two types of localised roof connection failures commonly occur at the roof sheeting to batten or purlin connections, known as pull-through failure and pull-out failure. In the pull-through failure, the screw fasteners connecting the roof sheeting to batten or purlin pull through the thin steel roof sheeting (Fig.2). However, suitable test and design method have been developed for pull-through failures (Beck and Stevens, 1979; Mahendran, 1990,1994; Mahaarachchi and Mahendran, 2004, 2009) while protective cyclone washers are also being used to enhance the pull-through capacity of those connections. However, this has then made the other localised roof connection failure, the pull-out failure, more critical.

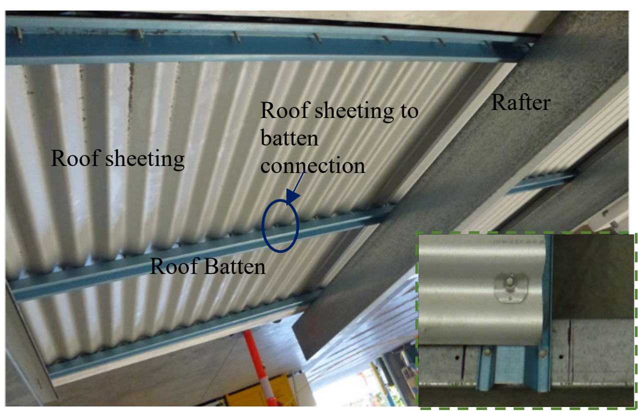

Fig. 1. Steel roof connections

In the pull-out failure, the screw fasteners connecting the roof sheeting to batten or purlin pull out from the thin steel roof battens or purlins (Fig.2). Recent wind damage studies have highlighted the occurrences of such localised pull-out failures, which caused partial or even complete loss of steel roofing systems. Mahendran and Tang (1998) experimentally investigated pull-out behaviour, but their study was incomplete. Therefore, a detailed experimental study consisting of 187 pull-out tests was conducted using a range of screw fastener types and sizes

(Table 1) and many thicknesses of steel roof battens and purlins (0.55 and 0.75 mm thick battens, and, 1.0, 1.2 and 1.5 mm thick purlins) made of three high strength steels G450, G500 and G550. Another experimental study was also conducted to investigate the pull-out capacity of multiple screw connections (two or four) between the two batten bottom flanges and the rafter. This paper presents the details of these experimental studies into the behaviour of roof battens and purlins subjected to pull-out failures. It proposes suitable design to accurately determine the pull-out capacities of single and multiple screw fastener connections in thin steel roof battens and purlins.

Table 1: Screw Fastener Details

Screw Fastener	Screw Type	TPI	p (mm)	D (mm)	d_1 (mm)	DD (mm)
Teks	10g-16	16	1.59	4.73	3.51	3.85
	12g-14	14	1.81	5.39	3.99	4.70
	12g-24	24	1.06	5.42	4.32	5.12
	14g-10	10	2.54	6.38	4.61	5.15
	14g-14	14	1.81	6.18	4.79	4.98
	14g-20	20	1.27	6.17	4.95	5.98
T17	10g-12	12	2.12	4.86	3.25	0.00
	12g-11	11	2.31	5.60	4.07	0.00
	14g-10	10	2.54	6.38	4.61	0.00
Zips	M6-11	11	2.31	6.00	4.20	3.10
	12g-11	11	2.31	5.30	4.18	3.20
	14g-12	12	2.12	6.38	4.58	3.80

Note: TPI – Threads per Inch, p – Pitch, d – Thread Outer Diameter, d_1 – Thread Inner Diameter and DD – Thread Drill Point Diameter

Experimental Studies

Pull-out failures of roof battens or purlins occur under a tensile action in the screw fasteners connecting the roof sheeting to batten or purlin and a bending moment in the batten or purlin. Therefore, small scale roof batten pull-out tests using a single span system were conducted by simulating both screw fastener tension and batten bending actions (Fig. 2). The test screw fastener was inserted in the batten top flange at the mid-span and, was pulled up vertically using a special 20 mm diameter nut with a 1.5 mm thick steel plate welded to it. The nut with a 7 mm diameter hole at its centre was placed on top of the roof batten top flange and the test screw fastener was located through the centre hole and inserted into the batten top flange. The nut was then connected to a threaded rod and a tensile load was applied using a testing machine. Three or more tests were conducted in each case.

The effect of member bending action on the pull-out failures was first investigated by varying the batten spans (300 and 700 mm), which showed that the bending action of batten does not influence the pull-out capacity. Therefore a small scale roof batten test method based on 300 mm span batten subjected to a mid-span load via a single screw fastener was used to determine the pull-out failure loads.

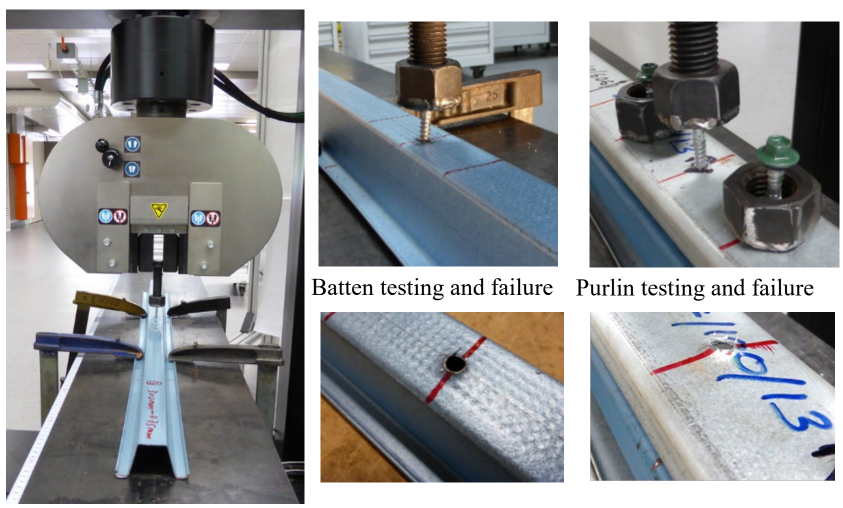

Fig.2 Pull-out tests of battens and purlins and failures

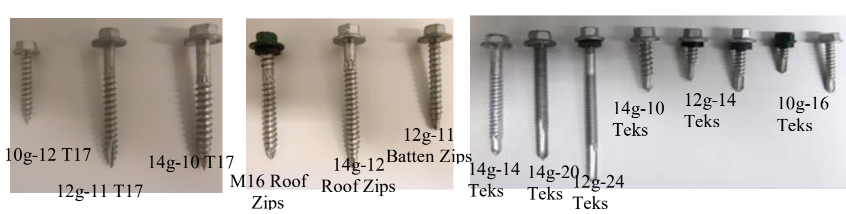

Fig.3 Screw fasteners used in the tests

Table 2: Mean Pull-out Capacity Results

d (mm)	p (mm)	t (mm)	f_u (MPa)	P_u (N)	P_u/ Eqs. 1 or 2	P_u/ Eqs. 3 or 4	P_u/ Eq. 8	P_u/ Eq.11
10g-16 (Teks)								
4.73	1.59	0.55	710	923.7	0.59	1.11	0.80	0.70
4.73	1.59	0.75	700	1478.6	0.70	1.32	0.87	0.76
4.73	1.59	1.03	590	2415.1	0.99	1.87	1.12	0.98
4.73	1.59	1.21	581	2510.2	0.89	1.68	0.96	0.84
4.73	1.59	1.52	551	3471.7	1.03	1.95	1.04	0.91
10g-16 (long Teks)								
4.73	1.59	0.55	710	895.6	0.57	1.08	0.78	0.68
4.73	1.59	0.75	700	1447.5	0.69	1.30	0.85	0.75
12g-14 (Teks)								
5.39	1.81	0.55	710	898.9	0.50	0.95	0.80	0.70
5.39	1.81	0.75	700	1370.8	0.57	1.08	0.82	0.72
5.39	1.81	1.03	590	2130.1	0.77	1.45	1.01	0.88
5.39	1.81	1.21	581	2519.3	0.78	1.48	0.98	0.86
5.39	1.81	1.52	551	3641.3	0.95	1.79	1.11	0.97
12g-14 (long Teks)								
5.39	1.81	0.55	710	883.4	0.49	0.93	0.78	0.69
5.39	1.81	0.75	700	1417.2	0.59	1.11	0.85	0.75
12g-24 (Teks)								
5.42	1.06	0.55	710	874.4	0.49	0.92	0.84	0.74
5.42	1.06	0.75	700	1365.7	0.56	1.07	0.89	0.78
5.42	1.06	1.03	590	1923.1	0.69	1.30	0.99	0.87
5.42	1.06	1.21	581	1895.9	0.59	0.77	0.80	0.70
5.42	1.06	1.52	551	3142.2	0.81	1.06	1.04	0.91
14g-10 (Teks)								
6.38	2.54	0.55	710	1361.2	0.64	1.21	1.00	0.87
6.38	2.54	0.75	700	1805.5	0.63	1.20	0.90	0.79
6.38	2.54	1.03	590	2207.0	0.67	1.26	0.86	0.75
6.38	2.54	1.21	581	3124.7	0.82	1.55	1.00	0.88
6.38	2.54	1.52	551	4132.9	0.91	1.72	1.04	0.91
Mean					0.77	1.43	1.00	1.00
COV					0.24	0.26	0.15	0.19

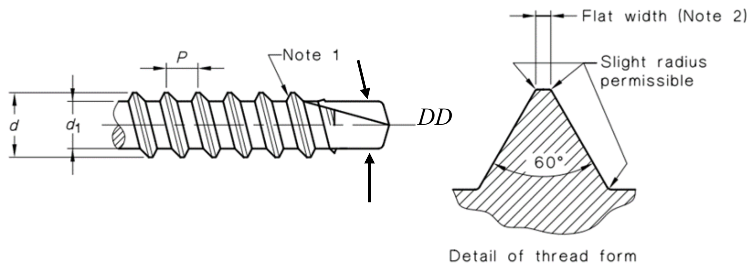

Fig.4 Screw fastener thread details: d – major (thread outer) diameter, d_1 – minor (thread inner) diameter, p – pitch and DD – drill point diameter

Following the initial investigations, the main roof batten pull-out tests were conducted for 14 different types and sizes of screw fasteners (Table 1). T17 screw fasteners are used to connect thin steel roof sheeting to timber battens or purlins. However, they are also recommended to connect the roof sheeting to thin steel battens (0.55 and 0.75 mm battens). Teks screws are used to connect roof sheeting to both thin and thick steel purlins. Zips screws were introduced recently to connect roof sheeting to either timber battens/purlins or thin steel battens/purlins. Figure 3 shows all the screw fasteners used in this research. Figure 4 and Table 1 present the other important screw fastener details such as pitch (p) and, outer diameter (d), inner diameter (d_1) and drill point diameter (DD) of the threads.

Tests of lipped channel roof purlins were also conducted (Fig.2) using eight suitable types of Teks and Zips screws. The bottom flange of purlin was restrained in position and the screw fastener was inserted into the top flange, and was then pulled vertically up. The purlin top flange was allowed to deform freely in the tests, reflecting the real situation. The test results are presented and discussed next.

Results and Discussion

Table 2 presents the mean pull-out failure loads obtained from the roof batten and purlin tests for selected combinations of batten/purlin thickness and screw type. Other details including all the test results are presented on our research group website (QUT Wind and Fire Lab, 2018). The pull-out failure modes of roof battens and purlins are essentially similar, but they can still be categorized into two groups. In most cases, they showed a permanent bending deformation of the top flange at the screw hole region whilst in a few other cases, they were observed without any significant bending deformation (Fig.5). In fact, the steel material trapped inside the screw fastener threads resists the applied tensile load and causes significant or insignificant bending deformation of the top flange based on the batten or purlin thickness. Mahendran and Tang (1998) defined these two failure modes based on the steel thickness (t) to thread pitch (p) ratio, ie. if t is less than p, it will cause a pull-out failure associated with a significant bending deformation of steel at the screw fastener hole and vice versa. The pull-out failure modes in this study agree very well with them. The pull-out failure modes in Fig.5(a) are related to t/p ratio values of 0.24 to 0.48 whilst this ratio is 1.20 for the pull-out failure mode shown in Fig.5(b). This confirms that when the t/p ratio exceeds one, the threads shear the steel material and cause pull-out failure without a significant bending deformation. However, when it is less than one, the steel material trapped inside the threads bears the load and causes a significant bending deformation before the pull-out failure. These pull-out failure mode observations lead to two theoretical approaches based on thread bearing and shearing of steel material.

(a)


(b)

Fig.5 Two types of pull-out failure modes (a) Thin battens (b) Thick battens

The pull-out failure load mainly depends on the steel thickness and grade (t and f_u in Table 2) and, screw fastener parameters relating to threads (Fig.4). The effect of steel thickness and strength on the failure load was significant and must be included in the pull-out capacity equations. However, since the screw parameters such as outer diameter (d), inner diameter (d_1), drill point diameter (DD) and pitch (p) of the thread vary among them, their individual effects on the pull-out failure load could not be investigated separately. However, some suitable test combinations were chosen to examine the effects of these important parameters. The 12g-11 batten zips and M6-11 roof zips have almost similar screw parameters such as pitch (2.31 vs. 2.31 mm) and inner diameter (4.18 vs. 4.20 mm) except the outer diameter (5.30 vs. 6.00 mm). Hence the test results obtained for these screws and 0.55 and 0.75 mm thick battens were used to examine the effect of d on the pull-out failure load. These results showed the effect of d is significant and it should be included in the pull-out capacity equations.

The difference between the thread outer and inner diameters (d-d_1) is likely to increase the pull-out capacity since it increases the steel material captured between the screw threads. This understanding indicates that smaller inner diameters (d_1) are likely to increase the pull-out capacity. To investigate this, only d_1 should be varied whilst keeping the other screw parameters constant. However, it was difficult to assess the effect of d_1 since it varies randomly with other screw parameters such as outer diameter, drill point diameter and thread pitch (Table 1). Therefore, a theoretical approach was considered next. The drill point diameters (DD) also vary randomly among the screws (Table 1). Although DD is smaller than d_1 for T17 and Zips screws, it is larger than d_1 for Teks screws. The effect of DD on the theoretical understanding of pull-out failure is also discussed next.

The T17 screw fasteners appear to provide higher pull-out failure loads compared to the same size Teks screw fasteners. This comparison highlights that the type of screw drill point (Fig.3) might have caused this difference in the pull-out failure load. However, since T17 screw fasteners are only used to fasten thinner steel battens and hence only a few test results are available, a separate categorization based on the type of screw fastener drill point was not considered.

Smaller thread pitches (p) are expected to increase the pull-out capacity. This is because more threads within the thickness increases the steel material captured between the screw threads. However, it was difficult to evaluate the influence of p separately, since it also varies randomly with other screw parameters (Table 1). Therefore, a theoretical approach was used and, the details are presented next. Same size screw fasteners are also available in different lengths (Fig.3). However, test results showed that the effect of screw fastener length is insignificant.

In summary, the steel material thickness and grade (t and f_u) and the screw fastener parameters such as thread outer diameter (d), inner diameter (d_1), drill point diameter (DD) and pitch (p) govern the pull-out failure loads and should be considered in the pull-out capacity equations. The screw thread parameters d, d_1 and p were considered as independent as indicated by the current thread designs.

Current Design equations

The pull-out failure loads obtained from the tests in this study (Table 2) were compared with the pull-out capacities (P_u) predicted using the design equations in the current cold-formed steel design standards, AS/NZS 4600 (Equation 1), AISI S100 (Equation 2) and Eurocode 3 Part 1-3 (Equations 3 or 4).

$$P_u = 0.85\ t\ d_f\ f_u \tag{1}$$

for t > 0.9 mm, where t - thickness of the sheet not in contact with screw fastener head, d_f - nominal diameter of the screw fastener ($3.0 < d_f < 7.0$ mm) and f_u - tensile strength of the sheet not in contact with the screw head in MPa.

$$P_u = 0.85\ t\ d\ f_u \tag{2}$$

where t - thickness of member not in contact with screw fastener head or washer, d - nominal screw fastener diameter ($2.03 < d < 6.35$ mm) and f_u - tensile strength of the member not in contact with screw head or washer.

$$\text{If } t / p < 1\text{: } P_u = 0.45\ t\ d\ f_u \tag{3}$$

$$\text{If } t / p > 1\text{: } P_u = 0.65\ t\ d\ f_u \tag{4}$$

where t - thickness of the member into which a screw fastener is fixed, d - nominal diameter of the fastener ($3.0 < d < 8.0$ mm), f_u - ultimate tensile strength of the supporting member into which a screw fastener is fixed and p - thread pitch.

The measured ultimate tensile strengths (f_u) of steels (Table 2) were used in these calculations. Table 2 shows significant overestimations and underestimations of the pull-out failure loads when these design equations are used. Equations 1 and 2 show a significant overestimation of 23% (mean and COV of average pull-out failure load/pull-out capacity ratio = 0.77 & 0.24) whilst Equations 3 and 4 show significant underestimations of 43% (mean and COV of average pull-out failure load/pull-out capacity ratio = 1.43 & 0.26). Although the comparisons made for Equations 1 and 2 based on the mean pull-out failure loads are valid, the comparisons made for Equations 3 and 4 require further modifications since the statistical level considered in the derivation of Equations 3 and 4 is different from that of Equations 1 and 2. In the latter comparison, the characteristic pull-out failure load should be considered instead of the mean pull-out failure load. Using a suitable reduction factor of 0.8 to allow for this difference (Eurocode 3, 2006) will effectively lead to underestimations of only 14% for Equations 3 and 4. However, the comparisons with Equations 3 and 4 still indicate a higher variation in the predictions of pull-out failure loads (ie. higher COV of 0.26). Since similar levels of variations were also observed by Mahendran and Tang (1998), they developed a new design equation to determine the pull-out capacities.

$$P_u = k\, d\, p^{0.2}\, t^{1.3}\, f_u \quad (5)$$

where k = 0.70 for thinner steel battens made of G250, G500 and G550 steel of thickness t < 1.5 mm; k = 0.80 for thicker steel purlins and girts made of G450 steel thickness 1.5 < t ≤ 3.0 mm; and k = 0.75 for all steel battens and purlins/girts made of G250, G450, G500 and G550 steels of thickness t ≤ 3.0 mm.

Although Equation 5 predicted the pull-out failure loads accurately with mean values ranging from 0.96 to 1.04 and COV values of less than 0.18, it was not developed in a non-dimensional format. Further, it did not include the new types of screw fasteners such as Zips screws. Further, their study did not investigate or include the effects of thread inner and drill point diameter. Hence this paper used the pull-out capacity test data from both this study (187 tests) and Mahendran and Tang (1998) (592 tests) to develop improved pull-out capacity equations.

Proposed Design Equations

The theoretical understanding of screw fastener pull-out behaviour is complex as it depends on many parameters such as thread design (inner and outer diameters, drill point diameter and pitch), thread length captured within batten/purlin thickness and steel strength. This can be defined into two cases based on the two observed failure modes: thread shearing and thread bearing. The pull-out force due to thread shearing can be determined by calculating the shear force needed to strip the steel material. The ASTM (FED-STD-H28/2B) presents Equation 6 to calculate this shear failure force F_s in N (Chapman et al. 1996, Patel et al. 2010)

$$F_s = S \times A_s = S \times \{L \times \prod \times D_{major}\} \times TSF \quad (6)$$

where S – material ultimate shear stress in MPa taken as 0.75 f_u, A_s – thread shear area, L – embedment length (mm), D_{major} – major (outer) diameter, ($L \times \prod \times D_{major}$) – area of a cylinder with a diameter of D_{major} and length of L, TSF (dimensionless) = 0.5 + 0.57735 d/p, d – thread depth (mm) = ($D_{major} – D_{minor}$)/2, D_{minor} – minor (inner) diameter and p – thread pitch (mm).

The pull-out force P due to thread bearing can be determined by multiplying the projected thread area by the material strength and number of threads in contact with the material (Juvinall and Marshek, 2010).

$$P = \prod/4 \times (D_{major}^2 - D_{minor}^2) \times \sigma \times (t/p) \quad (7)$$

where t, p, D_{major} and D_{minor} are as defined for Eq.6 and σ – bearing stress (equivalent to f_u – tensile strength).

The thread shearing case appears to be more suitable for thicker batten/purlins ($t>p$). However, since only a few cases depict this behaviour in this study, Equation 6 seems unsuitable for many cases (t/p ratio<1). Therefore, the thread bearing case (ie. Eq. 7) can be considered as a reasonable option to calculate the pull-out capacities. However, the pull-out capacities were determined using both Eqs. 6 and 7 and compared with the test results. As expected, Equation 6 predicted the pull-out failure loads with a lower test to predicted mean of 0.39 (overestimation of 61%) whilst Equation 7 predicted them with a higher test to predicted mean of 0.67 (overestimation of 33%). Overall, both equations failed to provide accurate predictions of the pull-out capacities of roof battens and purlins.

However, these equations highlight the effects of influential parameters on the pull-out capacity, ie. t, f_u, d and $d-d_1$ (increasing) and p (decreasing). Although all the current design equations (Eqs. 1 to 5) include the effects of t, f_u and d, only Eurocode equations (Eqs. 3 and 4) and Mahendran and Tang's (1998) Equation 5 include the effect of p. Although the Eurocode equations indicate that the pull-out capacity decreases with increasing pitch (same as theory), Mahendran and Tang's (1998) equation indicates an increment in the pull-out capacity with increasing pitch. This contrasting behaviour might have occurred since Mahendran and Tang (1998) did not consider the effects of thread inner and drill point diameters.

DeCoster et al. (1990) conducted pull-out failure tests for synthetic bone materials using both standard and custom made screw fasteners. Their test results showed that the pull-out capacity decreases with increasing thread pitch (p) whilst it increases with decreasing minor diameter d_1 (same as theory). Defino et al. (2007) investigated the effect of pilot hole size (drill point diameter DD) on the pull-out capacity of animal bones and stainless screws. They used a range of DD that are smaller and larger than the thread inner diameter d_1. Their test results showed that the smaller DD (smaller than d_1) provided higher pull-out failure loads. Oktenoglu et al. (2001) also showed that decreasing DD ($< d_1$) increased the pull-out capacity through their tests on cancellous bones. Since the effects of d_1, DD and p could not be investigated separately in our tests, the understanding gained from theory and past research studies was used in developing a new pull-out capacity equation by including the effects of p and ($d-d_1$) or (d-DD) on the pull-out capacity (P_u).

Considering the complicated nature of pull-out failures, the differences between theory and tests are more likely. Further, the design of screw fasteners (in terms of thread and drill point) appears to create such differences between theory and tests. The drill point in the Teks screws creates a pre-drilled hole initially, which eases the threading process, particularly in thick steels. However, no guidelines are available in AS 3566.1 (SA, 2002) or in the literature about the design of drill point and its sizes. However, Fig.4 from AS 3566.1 shows that the drill point diameter is equal to the thread inner diameter, which is not true for commercial screw fasteners (Table 1: larger DD than d_1). Since the pilot hole is created before the threading process, the larger DD creates a larger pre-drilled hole than d_1. This causes a small gap between the thread inner diameter and the steel at the inner diameter level and leads to a weaker steel connection for Teks screws. This issue causes inconsistencies in the pull-out failure loads from the many tests undertaken using Teks screws and also complicates the understanding of the pull-out failure behaviour. However, it is clear that drill point diameter (DD) should be considered instead of thread inner diameter (d_1) for Teks screws. In summary, the effect of (d-d_1) should be considered for Zips and T17 screws whilst the effect of (d-DD) should be considered for Teks screws in the new pull-out capacity equation.

The above discussions show the necessity of developing new design equations for the pull-out capacities of all the types of screw connections in thin steel roof/wall cladding systems based on only the most critical parameters such as t, f_u, d, d_1, DD and p. The efforts were first made to modify the current design equations (Eqs. 1 or 2). Although it was possible to achieve a mean of 1.00 by reducing the constant from 0.85 to 0.65, it will still have a higher COV of 0.24 and high error margins (+58% and -77%). Therefore, engineering curve fitting technique was used to obtain improved pull-out capacity equations (Equation 8). The effect of d_1 was considered for Zips and T17 screw fasteners, while the effect of DD was considered for Teks screw fasteners.

High strength steel roof battens/purlins with $t \leq 1.52$ mm:

$$P_u = 1.42\, t^{1.3}\, d^{0.7}\, f_u\, [(d-d^*)/p]^{0.3} \qquad (8)$$

where d^* = larger of d_1 or DD (d_1 for Zips & T17 screws; DD for Teks screws)

Equation 8 provides better predictions of test pull-out failure loads with overall mean and COV of 1.00 and 0.15 (Table 2) and can be used to predict the pull-out capacities. However, since it is limited to purlin thicknesses up to 1.5 mm, the 592 pull-out capacity data from Mahendran and Tang (1998) for battens and purlins (thicknesses of 0.4 to 3.0 mm and steel grades of G250 to G550) and T17 and Teks screw fasteners (10g to 14g) (not Zips screws) were also considered. Suitable design equations were first developed using only their data. Since they conducted pull-out tests using both high strength (G550, G500 and G450) and low strength (G250) steel roof battens and purlins, design equations were developed separately.

High strength steel roof battens/purlins with $t \leq 2.93$ mm:

$$P_u = 1.65\, t^{1.3}\, d^{0.7}\, f_u\, [(d\text{-}d^*)/p]^{0.3} \tag{9}$$

Low strength steel roof battens/purlins with $t \leq 0.95$ mm:

$$P_u = 1.85\, t^{1.3}\, d^{0.7}\, f_u\, [(d\text{-}d^*)/p]^{0.3} \tag{10}$$

Both Equations 9 and 10 predicted the test pull-out failure loads with the same mean and COV of 1.00 and 0.16. They show good agreements except the constant (1.42 versus 1.65 and 1.85). Finally Equation 11 was developed by considering all the 779 test data from this study and Mahendran and Tang (1998).

$$P_u = 1.62\, t^{1.3}\, d^{0.7}\, f_u\, [(d\text{-}d^*)/p]^{0.3} \tag{11}$$

Equation 11 predicted the test pull-out failure loads with mean and COV of 1.00 and 0.19. Although the COV has increased to 0.19, this design equation covers a wide range of thin steel roof/wall connections (both high and low strength steels- G250, G450, G500 and G550, thicknesses from 0.4 to 3.0 mm and 17 types and sizes of screw fasteners). Figure 6 compares the pull-out capacities predicted using Equation 11 with test pull-out failure loads.

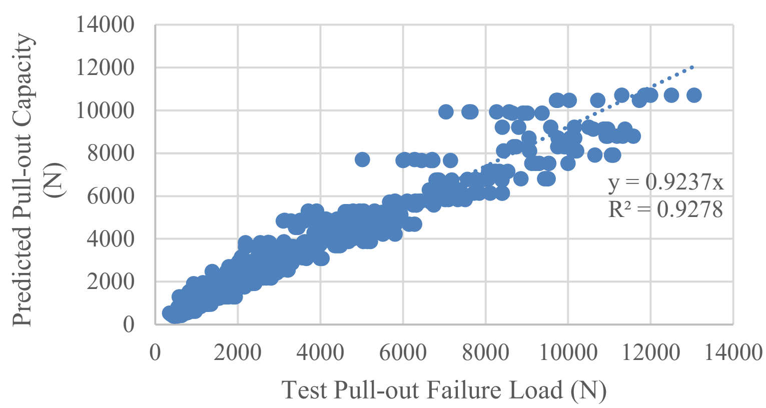

Fig.6 Comparison of pull-out failure loads with Equation 11

The accuracy of the curve fitting process used to derive Equation 11 was found to be adequate when assessed independently by choosing and comparing suitable test combinations. However, comparisons made for thinner high strength steel thicknesses (0.43 to 0.75 mm) showed that the predictions are not as accurate as for low strength steels and thicker (≥ 0.95 mm) high strength steels. The reduced ductility of thinner high strength steels might have caused this. Since Equation 11 was derived using many low strength steels and thicker high strength steels, the power coefficient of one can still be considered suitable overall. To allow for the reduced ductility effect, AS/NZS 4600 suggests suitable reduction factors, 90% of f_u for $t < 0.9$ mm and 75% of f_u for $t < 0.6$ mm. However, our pull-out test results showed the possibility of using larger reduction factors than those given in AS/NZS 4600. Hence Equation 12 is proposed by including a new factor, k, in Eq.11 to allow for the effects of ductility. The test to predicted ratios were used first to choose the relevant steel groups, and then suitable predictive equations were developed for each group, from which the required k factor was determined.

$$P_u = 1.62\ k\ t^{1.3}\ d^{0.7}\ f_u\ [(d\text{-}d^*)/p]^{0.3} \qquad (12)$$

where k = 0.88 for $t < 0.9$ mm high strength steels (G550), 0.96 for 0.9 mm $\leq t \leq$ 1.21 mm high strength steels (G550 and G500), 0. 91 for $t \leq 1.21$ mm high strength steels (G550 and G500), 1.07 for 1.21 mm $< t \leq 2.93$ mm high strength steels (G450) and 1.14 for low strength steels (G250).

To calculate design pull-out capacities, a suitable capacity reduction factor is required. For this purpose, the procedure in AISI S100 Chapter F was used, which gave a capacity reduction factor of 0.55 for use with Equation 11. The same factor (0.55) can also be used with Equation 12 conservatively. However, accurate capacities can be determined by using the relevant k factors and corresponding capacity reduction factors (0.56, 0.57, 0.56, 0.58 and 0.58 for the five cases).

Multiple Screw Connections

Previous sections of this paper have discussed the pull-out capacities of single screw connections between roof/wall sheeting and battens/purlins. However, batten to rafter connections include one or two screws on each bottom flange (total of two or four screw connections) as shown in Fig.7. A series of 80 pull-out tests of such multiple screw connections was undertaken to determine their pull-out capacities (Fig.7). Test results showed that their capacity cannot be obtained by multiplying by the number of screw fasteners. It was found that the total pull-out capacity of roof batten to rafter connection improves by only 40 and 29% when two- and four-screw connections were used. A suitable reduction factor was therefore introduced to Equation 11 to determine the pull-out capacity per fastener in multiple screw connections. Using the test results, it is recommended that reduction factors 0.70 and 0.45 are used with Equation 11 to determine the pull-out capacities of two- and four-screw connections.

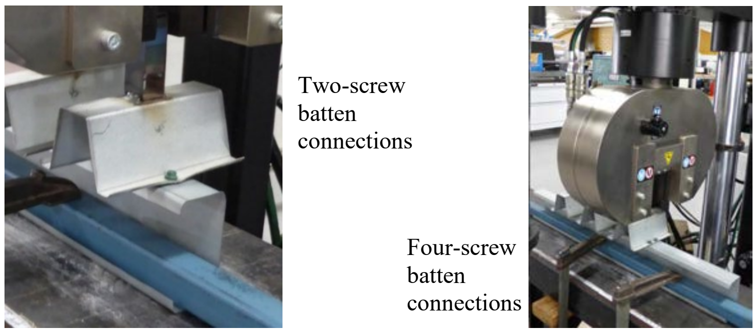

Fig.7. Multiple screw connection pull-out tests

Conclusions

This paper has presented the details of a detailed experimental study on the pull-out failures occurring in the thin steel roofing systems including the effects of steel thickness and strength, screw fastener thread outer diameter, inner diameter, drill point diameter, drill point type and thread pitch. The design equations available in the current cold-formed steel design standards were found to be inadequate in accurately predicting the pull-out capacities. The use of available theoretical approaches was also shown to be inadequate. Suitable design equations and capacity reduction factors were then developed for single and multiple screw connections using the pull-out failure test results. For cyclic wind uplift loads, fatigue effects should be included based on Mahendran and Mahaarachchi (2002) who recommend a conservative reduction factor of 0.30. The new design equations can be satisfactorily used to design safer steel roof cladding systems subject to high wind uplift loads. They can also be used to design safer wall cladding systems subject to high wind suction loads.

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